condensation. This fully explains the greater rise of "potential temperature" in the lower strata.

Air passing horizontally near the surface is gaining heat when going toward the Equator. This is natural enough, for a north wind is naturally cold and is being warmed by its surroundings. The converse also holds.

The most interesting case is that of the horizontal passage of air north and south at great heights. The temperatures above 17 kilometers at the Equator must be accepted with great reservation, since observations are very scarce, but from about 12 to 17 kilometers the equatorial potential temperatures are certainly much below the others. The pressures are greater also, so that the flow of air should be toward the north. If the flow is toward the north the air is gaining heat and it seems to me that from its situation it ought to be doing so. It is very cold and therefore is not itself radiating much either upward or downward, and it has passing through it outward the whole radiant energy which is being sent outward by the earth and by the four-fifths of the atmosphere which lie below it, and much of which is at a far higher temperature. It is likely to be a long time before any direct observations can show which way the drift is, for a very slow motion will suffice to explain the low actual temperatures over the Equator. The general motion is from the west, and it is a question whether on the balance over the whole zone the direction is a few degrees north or a few degrees south of west. The ascending current over the Equator is certainly slow, a hundred feet a day, perhaps, or something of that sort; otherwise the temperature gradient would be steeper; and the air carried up by so feeble a draft could readily escape north and south without detection, even if we had as precise observations of the upper winds as we have of the surface winds.

Reverting to the actual temperatures, it is noteworthy how similar the temperature gradient is in the two localities. It begins at about 5°C. per km., then after the cloud level, excluding cirrus, is passed it increases to 7° or 8° per km., up to the point at which it stops altogether. This point is higher the lower the latitude. Observations from all parts of the world show the same tendency, except that where the surface temperature is very low the gradient in the lower strata is absent or reversed.

It seems to me likely that this special form of gradient is a sort of compromise between two opposite tendencies. It is obvious that if the air could be thoroughly mixed up, the adiabatic gradient would prevail throughout, for the mixing will make equal potential temperatures, just as stirring the water in a bath makes a uniform temperature. Now, the winds, however they may be caused, must do a certain amount of mixing and hence must raise the bottom temperature and lower the top; and unless there were something else to reverse the result the process would go on until the gradient were adiabatic. But radiation checks the result, I believe, for in my opinion the tendency of radiation is toward a uniform temperature or to a small gradient. The argument seems clear that the winds alone must make an adiabatic gradient, since they do not do so something must interfere with the process and that something can be nothing else save radiation. It is significant, too, that observation shows that the wind falls off rapidly at or about the point where the temperature gradient ceases.

The statement previously made that upper-air temperatures depend on the pressure distribution rather than on radiation is based on the following facts. So many observations have been made over Europe, ranging from Pavia in the south to Petrograd in the north and from Ireland in the west to Russia in the east, that we have quite a good knowledge of the conditions both in summer and winter and in times of cyclonic and of anticyclonic weather. Over the British Isles solar radiation in summer is about three times as great as in winter and the temperature of the air up to 10 kilometers is in general 12°C. (21°F.) warmer. Nothwithstanding this, for the purpose of knowing the most likely temperature of the upper air, it is more important to know the height of the barometer than to know the time of the year, for after the first kilometer or two is passed the air in a well-marked cyclone will be colder in summer at from 3 to 7 kilometers than it is at the same height in winter in anticyclonic weather; and above 12 kilometers the converse will hold. The same rule holds for Europe generally, but cyclonic conditions there are much less frequent. Moreover, it is not the pressure at sea level that is important, but the pressure at about 8 or 9 kilometers. The temperatures both above and below follow the variations of pressure at 9 kilometers with the utmost precision, and if a chart showing pressures at 9 kilometers could be given it would be easier to draw a chart of temperatures at 5 or, to a less extent, at 15 kilometers than it is to draw a chart of wind forces and directions from isobars on an ordinary chart. The pressure at about that height seems to dominate all the other elements.

FORECASTING THUNDERSTORMS.[1]

By GABRIEL GUILBERT.

[Dated Aug. 3, 1912.]

1. Wireless telegraph installations are known to possess the curious property of recording [indicating] the electrical manifestations produced in their neighborhood and even at very great distances.

Thus, on March 4, 1912, a formidable thunderstorm accompanied by trombes descended upon Calvados [Département Caen] at about 19h and a meteorologist of the Lyon observatory, M. Flajolet, simultaneously observed his wireless apparatus to record powerful distant phenomena.

It was but a step from this observation to the thought that it would be possible to announce for a given point, the approach of a distant thunderstorm indicated by the wireless outfit, and physicists such as M. Turpain of Poitiers have attempted these predictions.

So far it has not been possible, unfortunately, to forecast the direction of these distant thunderstorms. Thus, in the case of the squall of March 4, 1912, the apparatus at Lyon did indeed record the existence of a storm, but could not indicate whether or no the storm was approaching the observatory. As a matter of fact it was traveling toward the NNE. part of France and was moving away from Lyon. The wireless telegraph remained and will remain mute, powerless, on this essential point as well as on the speed of the storm.

Certain squally clouds are indeed either very slow moving or very rapid; they may move at the rate of 20 or of 100 km.-hr.; wireless telegraphy knows nothing as to that and can not know anything.

On the other hand, certain meteorologists believe that they can notice that the wireless apparatus also reacts to phenomena quite other than thunderstorms; there is thus

[1] *Translated from* Association Française pour l'avancement des sciences, Compte rendu, 41me sess., Nîmes, 1912. (Paris, 1913), p. 296-304.—C. A., jr

some uncertainty as to the significance of the indications of the apparatus. Finally, the wireless can not announce the passage of thundersqualls *not yet in existence*, e. g. 24 hours before they develop, or even of thunderstorms raging in some undetermined direction, a direction all the more indeterminate because several thunderstorm centers (centres orageux) may exist simultaneously and either to the north or to the south of the station at some unknown distance.

2. So it is that if one wishes to predict the squall not merely some hours in advance, but even in the evening for the morrow, it is necessary to resort to the rational study of isobaric charts, of barometric depressions, of squall lines or zones,[2] and to supplement these by a methodical examination of the clouds.

3. Thus always, whatever method one may choose, the forecasting of thunderstorms for any given locality will always be very deceptive. Failures will be frequent for the simple reason that the thunderstorm takes place in clouds of limited extent which therefore most frequently visit but a small number of points in the region under consideration. On the other hand the failures will be very rare if one admits that the passage of a single thunderstorm at a single place in the designated region is a sufficient justification for the forecast "Thunderstorms."

4. The majority of meteorologists group thunderstorms into two principal classes: The thunderstorms accompanying a depression, and local thunderstorms; or even into winter thunderstorms and heat thunderstorms. To the writer these distinctions seem but little justified and even arbitrary. Thunderstorms that accompany, in effect, the depressions of winter or of summer are sometimes very local while in other cases thunderstorms pursue very long courses without any accompanying sensible depression. Therefore this classification is defective, as for the so-called heat thunderstorms, or those whose principal cause is supposed to be a very high temperature, their relation to the temperature is not at all proved.

[A] The warmest days often fail to bring about any electric manifestation at all, and the warmest months are those most free from thunderstorms, as we have shown.[3] The name "local thunderstorm" would therefore appear to be more correct. Yet another designation is current "the thundersquall" (l'orage de grain). In its relations to barometric depressions this is a cyclonic thunderstorm in winter, a depressionary thunderstorm (orage dépressionaire) in summer, and never a heat thunderstorm.

5. If the thunderstorm produced only lightning or thunder, it would be of only relative importance, but it may bring along a whole series of redoubtable phenomena. Its prediction calls out the possibility of wind blasts as sudden as they are violent, torrential rains and floods, disastrous hail falls, whirlwinds or tornadoes of frightful force. These catastrophes are possible at any time of year. Hail or whirlwinds may occur whatever the temperature. No doubt one notices hail particularly during the summer because it then causes the greatest damage to vegetation, but hail falls at all seasons of the year.

The forecasting of thunderstorms implies the forecasting of all these phenomena, which are the possible consequences of magnetic manifestations. As a matter of fact, however, these accessory phenomena are rare. The violence of the wind is not often dangerous. Among 10 thunderstorms there is scarcely one that brings a fall of hail; among a thousand there is perhaps one whirlwind. To be sure, these ratios vary according to the regions and even according to the observatories. They would be considerably heightened if one compared the number of hail falls or the development of whirlwinds, not with the number of zenithal thunderstorms but with the number of days of thunderstorms recorded in a more or less extensive region such as a "Départment." Then one would find hail falls once in 5 and whirlwinds once in 100 cases.

6. We are not here concerned with statistics, however, for at the present time it is not possible to forecast either hail falls or tornadoes. We are simply able to predict the thunderstorm, or rather the passage of squally clouds liable to be the seat, at one point or another, of electric manifestations and also the accessory phenomena such as hail, wind squalls, or tornadoes. The thunderstorm brings them all in its train; it may produce them simultaneously or fail to give any of them expression. There is, therefore, complete uncertainty as to the atmospheric disturbances that may accompany the thunderstorm.

7. Some secondary phenomena are always regularly observed, without exception, in thunderstorms.

In the first place there is a change in the wind, both as to direction and to velocity. For example, the wind changes from S. to W., returning to SW., and from being weak it becomes strong, only to weaken anew. The barometer is usually low, rises brusquely, soon to become stationary, then falls again. The temperature drops notably, while the hygrometric condition rises. As is well known, these characteristic variations have been extensively studied by Durand-Gréville, author of "Loi des grains" (Law of Squalls). The thunderstorm is no longer the principal phenomenon; it is the accessory and the consequence of a squall. It is the squall that determines the thunderstorm and, even in the absence of the latter, produces the variations in wind, pressure, temperature, atmospheric humidity, cloudiness.

Even though these phenomena affect diverse forms and develop successively, the squall nevertheless exists. M. Durand-Gréville has here established, from a very large number of observations, an undoubted ensemble of features which in my opinion permit the differentiation of the principal barometric depression, of the secondary depression, and of the *squall*, whose existence is undeniable. From the present point of view, however, i. e., the forecasting of the thunderstorm, the study of the squall is secondary. **[B]** According to Durand-Gréville himself, the squall (grain) is not the actual cause; it is not able to produce the thunderstorm except under the conditions where it meets with cumulus having very lofty summits. So that lacking this cumulus the squalls or the squall zones can not produce the thunderstorm. Therefore the atmospheric phenomena constituting the squall (grain) can not serve to forecast nonexistant thunderstorms, and all the less to forecast thunderstorms for the next day. Furthermore, the squall, like all cyclones and depressions, may have but an ephemeral existence. It may develop or it may diminish and disappear after having traversed a more or less extensive path. It would be venturesome to conclude, from its presence at one point, that a squall would pass over some other region after a given time, and all the more so since its speed of translation is unknown.

Again, the thunderstorm is not bound solely to the squall line or the squall zone. It may develop even at the center of the cyclonic whirl; each thunderstorm cloud may be the center of a vertical motion, and the passage

[2] These terms were defined and illustrated in this REVIEW, June, 1909, 37: 237-39.—C. A., jr.

[3] Not the case for the United States of America. See *Alexander* in the REVIEW, July, 1915, 43: 326-340; and *Lyman* in this REVIEW, December, 1915.—C. A., jr.

of every cyclone over any point produces exactly the same phenomena that one would exclusively attribute to a squall. With or without a thunderstorm one would note a sudden and sometimes overwhelming increase in the wind velocity and its direction; the sudden rise in the barometer; the equally sudden fall in temperature; the corresponding rise in the hygrometric state and in the cloudiness.

All these phenomena may be observed, with appropriately decreased intensity, out to a considerable distance from the cyclonic center, without it being necessary to call in a squall line. One must therefore conclude that the *cyclone* of vast extent, the *depression* or small-scale cyclone, and the *squall* (grain) or yet more limited atmospheric whirl, and even the imperfect *vortical wave* are distinct phenomena identical in nature and therefore able to produce identical perturbations.

8. Thus M. Durand-Gréville has very truly stated that a thunderstorm can not develop unless, previous to any barometric condition, there exist a *great cumulus with very lofty summits*. I am wholly of his opinion. The presence not of cumulus but of *cirro-nimbus* is the essential condition for the thunderstorm, and it is therefore quite logical to make the forecasting of thunderstorm clouds the fundamental basis of thunderstorm forecasting.

9. If there is one fact that ought to attract the attention of meteorologists, that is the similitude of cloud forms at all seasons of the year. Cirrus, cirro-cumulus, alto-cumulus, and cumulus present the same aspects on the most rigorous winter days as on the warmest days of summer. A priori, a similar observation, seems to demonstrate that the formation of clouds is independent of the air temperature at the earth's surface. Clouds would accordingly develop in a cold atmosphere, so cold, in fact, that in my opinion they would never produce rain, but always snow. Furthermore, the thunderstorm clouds, which obey the same law and present characteristic forms at all seasons, are of the upper clouds, composed of ice crystals or of snow, and which we designate for that reason *cirro-nimbus*.

This cirro-nimbus always forms a part of the company of clouds that we call the "cloud succession" (succession nuageuse) and which comprises the cirrus, cirro-cumulus, cirro-stratus, alto-cumulus, and finally the cirro-numbus. Lacking the presence of these latter clouds, it must be stated as a principle that any thunderstorm is impossible, that it will never burst forth in the cirro-stratus or in the cumulus whatever be their extent. Even more, whatever be the barometric depression, the squall zone, the visible clouds, the temperature, if cirro-nimbus can not exist the thunderstorm is impossible.

On the other hand, if the "cloud succession" calls for cirro-nimbus, all the thunderstorm phenomena become possible, although not assured, and this holds whatever may be the atmospheric situation.

It results from this postulate, which I published in 1886 [4] and which is confirmed by each day's experience, that the cause of the thunderstorm is to be sought solely in the structure, the composition or the physical changes in that strange cloud, and that the prevision of the thunderstorm should be united with the prevision of the arrival or passage of the cirro-nimbus.

This prevision is all the more possible since the thunderstorm cloud is the *last* in the "cloud succession." It is always preceded by the cirrus, the cirro-cumulus, the alto-cumulus. Thus it does not arrive unheralded, does not spring into being without any notice in advance, it does not burst forth in the bosom of a cumulus due to high temperature nor in an atmosphere *appropriately prepared*.

One of the most convincing proofs of this statement is to be found in the observation of the speed of the first clouds of the "cloud succession." If the cirrus is driven at great velocity, the cirro-nimbus which should follow it will also have a rapid movement; if the preliminary cirrus moves slowly, the thunderstorm clouds in their turn advance more slowly. This relation between the velocities of successive cloud classes, and which endures a number of days, excludes all idea of a local formation.

10. As the plan of this study does not permit of reviewing all the cases of agreement or disagreement between different clouds and the depressions, we shall confine ourselves to the cirro-nimbus in its seasonal relations to the thunderstorm.

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11. In general, showers (averse) or rains of short duration, which are often abundant and sometimes torrential, are due to the passage of the cirro-nimbus. Therefore all forecasts of showers imply the forecast of thunderstorm phenomena; therefore one should predict, not "showers," but thunderstorm showers. [C] Also, therefore, the forecast of thunderstorm showers is synonymous with the forecast of squalls. In fact, in the mariner's language the squall is nothing more than the passage across the zenith of a cloud with showers in a clear sky. This cloud unchains violent wind gusts, obliging the mariner to reef his sails, and even to furl them. When the shower is over, the weather changes to fine again and the wind, which is then almost always between SW. and NW. or N., diminishes its force until the return of another cirro-cumulus provokes another squall, i. e., a renewed gust accompanied by sensible changes in wind direction and often barometric oscillations also.

Thus all showers are due to squalls, and it is in these squalls that occur most of the winter thunderstorms, which generally consist of a few isolated peals of thunder.

We propose as a thesis, *that all winter storms are* accompanied by thunderstorms. Thus the stronger the depression during the cold season (November to March) the better the chance of success for the thunderstorm forecast. These cyclonic thunderstorms arise most frequently where the wind changes from S. to W., or from SW. to NW. They chiefly visit the regions neighboring the sea. [Conditions of western Europe.]

12. March, which closes the cold season, is the month par excellence of the hail shower (giboulée). These showers, with their generous hail falls, are often thunderstormy. They belong to the cyclonic régime: The deeper the depression, the more numerous are the thunderstorms within the dangerous semicircle of the cyclone, and in the rear of the center.

13. From the thunderstorm point of view, the summer may be said to begin with April and to close with the autumnal equinox.

While during the winter the thunderstorm shower rarely appears other than in the rear of the depressions, the summer thunderstorm may occuppy even the center of the cyclonic whirl. In winter the wind and the thunderstorm follow the same direction, within a few degrees; but in summer the thunderstorm moves against the wind or makes more or less of an angle with the latter. In winter the thunderstorm always accompanies or follows

[4] Annuaire de la Société météorologique de France, avril, 1886.

very closely after a violent cyclone; but in summer the weakest depression may produce a thunderstorm.

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14. It is somewhat easy to forecast thunderstorms when the summer depressions appear over the southern regions of France; but it is much more difficult when a depression, over the Gulf of Gascony for example, suddenly disappears.

Although the pressure may be higher to the north, e. g., 770 mm. at Dunkirk, 765 at Mans, 760 at Biarritz, there is no cyclonic center. Under such circumstances the "cloud succession" alone furnishes a basis for a forecast. In fact, it is scarcely admissible that a depression should appear without a cloud accompaniment. If, in spite of the barometric rise, the cirrus, cirro-cumulus, alto-cumulus appear in regular succession, in the same direction from southerly points northward, and in spite of easterly winds, then it is infinitely probable that the cirro-nimbus will follow them in its turn. Therefore, even after the depression has disappeared, even in the case of a barometric rise (slight to be sure), even in the absence of the "squall zone" or of V-shaped isobars, yet the existence of a "cloud succession" would suffice to foretell the thunderstorm. Thus came in the too-famous thunderstorms of July 29, 1892, June 6, 1904, July 4, 1905, June 30, 1908, etc., all of which were characterized by an extraordinary violence in spite of the absence of sensible depressions and even in the face of high pressures with rising pressures. In fact these examples justify one in setting up the thesis that *the intensity of electric phenomena increases with the rise of the pressure.* A thunderstorm occurring in the summer with the barometer about 765 mm. will cause more ravages by rain, hail, or lightning than if the pressure had fallen to 755 or thereabouts.

15. [**D**] There is no occasion to introduce here hypothetical phenomena which, moreover, do not demonstrate anything: Such as the rapid descent of a sheet of air to the ground, or the precipitation of cirrus upon subjacent cumulus. The most attentive observation does not reveal any disturbance of this nature. The cooling frequently observed after the thunderstorm is often due to the change in the direction of the wind, a cyclonic phenomenon, and also to the sudden melting of a prodigious quantity of ice or snow crystals. The consideration of the vortical character of the squall offers a very simple explanation of the barometric variations and the fall in temperature as well as of the increase in cloudiness.

16. While the depressions of Gascony and the summer "cloud succession" of the south of France are the greatest sources of thunderstorms for almost the whole of France, there is yet another very remarkable thunderstorm formation, viz, the arrival of Saharan depressions upon the coast of Provence. As soon as a cyclonic center persists in that region, with cirrus and then cirro-cumulus from the SE. changing to E., we have to expect thunderstorms between the SE. and NE. throughout France accompanying winds from the east as well as from the west.[5]

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17. To sum up, all thunderstorm forecasts should be based upon a simultaneous study of the barometric situation and of the cloud successions. The study of the isobaric map should lead to a forecast of the future pressure distribution, of the formation of depressions, and of squall zones for the next day. The study of the cloud succession ought to show whether or not *cirro-nimbus* should develop and also whether or not it will coincide with the depression centers on the morrow. The clouds indicate, better than do the depressions, the direction and speed of tomorrow's expected thunderstorm. On the day itself a station can determine this speed and direction only shortly before the arrival of the storm. [**E**] The consideration of the squall zone is insufficient, for its trajectory is indeterminant while the thunderstorm pursues a straight-line course, or at most a curve of very large radius, which neither the topography nor tidal movements nor even the manifold directions of the surface winds can deflect. Hail-falls and paths of destruction by tornadoes always make straight lines, which confirms these conclusions based on direct observations. Successive thunderstorms, even though each occupy the center of a slightly whirling movement having variable winds in all directions and with the lower clouds from an opposite direction, nevertheless advance in the direction indicated 24 to 48 hours previously by the upper clouds.

The thunderstorm, the *cirro-nimbus,* thus exist only in the higher levels, so that it is not possible to have any means of influencing either their direction or their effect. And yet the thunderstorm is of very limited duration, at most it may last 24 hours, generally a few hours suffice to exhaust it.

Perhaps the progressive descent of the upper clouds is a cause of its destruction. One has thus observed extensive thunderstorm clouds moving from S. to N. with lightning and thunder, dissipating, dissolving, even disappearing, with more or less observable delay, under the action of very dry winds from the N. or NE. The thunderstorm cloud subsists in the southerly current, but very probably experiences an evaporation as it attains the northerly current. The thunderstorm ceases while the thunderstorm cloud steadily fades away.

[5] The direction of the thunderstorm cloud, cirro-nimbus, is often independent of the trajectory of the cyclonic centers and of the squalls, therefore also independent of the surface winds.—AUTHOR.

COMMENTS BY DURAND-GRÉVILLE.

[The foregoing paper by M. Guilbert called out the following comments by M. Durand-Gréville,[1] whose studies in thunderstorms, squalls, and hail have already been noticed here (1909, **37:** 237–239). References are to the passages marked by corresponding letters in M. Guilbert's paper.—C. A., jr.]

In a memoire "On the forecasting of thunderstorms," published in this volume, M. Guilbert puts forward his own ideas and rejects some of mine, which he has a perfect right to do; but he states my views in such a summary and fragmentary manner that the unwarned reader might not understand exactly what I hold in this connection. The present note designs less to present a fundamental discussion of our colleague's theory than to present our precise opinion concerning certain of the points that he discusses.

1. *Guilbert* says (**A**, p. 557):

> The warmest days often fail to bring about any electric manifestation at all, and the warmest months are those most free from thunderstorms, as we have shown. The name "local thunderstorm" would appear to be more correct (than that of heat thunderstorm).

Durand-Gréville.—The thunderstorm is an electric disruptive discharge between the negative electricity of the earth's surface and the positive electricity of the cirrus region. The discharge does not take place unless a sufficient communication is established between the two levels. This communication is realized every time

[1] Mise au point de quelques objections à notre théorie des grains et de la grêle. Assoc. franc. pour l'avance. d. sci., Compte rendu, 41[me] sess., Nîmes, 1912, Notes et Mémoires (Paris, 1913), p. 286–291.